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UTILITY APPLICATION FOR UNITED STATES PATENT  
FOR  
DEVICE FOR CONFINEMENT OF A PLASMA WITHIN A VOLUME

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DEVICE FOR CONFINEMENT OF A PLASMA WITHIN A VOLUMEGeneral technical domain

This invention relates to the general technical domain of plasmas, from the lowest pressures ( $10^{-6}$  or less) up to pressures of the order of  $10^{-2}$  torr.

More precisely, the invention relates to complete or  
5 partial confinement of plasma in a volume, and particularly confinement in large uniform plasma volumes at low and very low pressures.

The invention is advantageously used in applications for all techniques that require firstly production of dense  
10 and uniform plasma, and secondly confinement of this uniform plasma in a chamber, for example in which the application is taking place.

Remember that plasma is a conducting gaseous medium composed of electrons, ions and neutral particles,  
15 macroscopically electrically neutral. Plasma is obtained using an electric field, by ionisation of a gas by electrons accelerated in this electric field.

For some applications, it may be desirable to confine plasma in the volume of a chamber.

Plasmas may be confined in a volume using permanent magnets.

5        In this case, confinement is usually done by placing permanent magnets at the periphery of the confinement volume (inside or outside the chamber walls) with alternating north and south polarities facing the plasma. Therefore the periphery of the chamber is subjected to a  
10        magnetic field. This technique is called "multipole magnetic confinement".

The principle of multipole confinement of "charged species" particles forming the plasma is as follows.

15        The charged particles in the plasma move in the chamber between peripheral regions subjected to the magnetic field formed by the permanent magnets and central regions not subjected to the said field.

20        The charged particles entering the region of influence of a multipole magnetic field are subjected to three main mechanisms.

1/ Mechanism 1. Charged particles output from a region in which there is no magnetic field may be reflected on and by the magnetic field and may return into the region not subjected to the magnetic field;

25        2/ Mechanism 2. Charged particles output from a region in which there is no magnetic field all enter the region of the magnetic field, when their path is almost parallel to the magnetic field lines.

30        Charged particles subjected to mechanism 2 are lost for the plasma. These particles arrive in a region in which

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there is no magnetic field and move towards regions of convergence of the magnetic field lines, in other words either directly on magnetic poles of magnets (where the magnetic intensity is maximum) or between two magnets with  
5 the same polarity, where the magnetic intensity is minimum and zero. The paths of charged particles are then parallel to the magnetic field. If magnet poles are located on the walls of the chamber, the particles passing through this area will for example strike the walls of the chamber. This  
10 is the case particularly for areas located between two unit magnets with alternating polarities.

Convergence areas of magnetic field lines are called "festoons".

3/ Mechanism 3. This is a trap for charged particles  
15 in the multipole magnetic field using a collisional mechanism.

Figure 1 shows that once high energy electrons are trapped in the magnetic field, and are in an interval between two elastic or inelastic collisions, they oscillate  
20 between two magnetic field lines and two mirror points M, at which the magnetic field intensity is identical. These mirror points M face two opposite magnetic poles of the same magnet or of two adjacent magnets.

High-energy electrons that produce the plasma, called  
25 fast or primary electrons are not very sensitive to the self-consistent electrical field produced by the plasma space charge.

On the contrary, the low energy ions and electrons in the plasma, also called slow or thermal electrons, also  
30 oscillate between two opposing magnetic poles, but they are

also sensitive to the self-consistent electrical field produced by the plasma space charge. Consequently, they then diffuse collectively in the magnetic field under the influence of this electrical field, preferably to areas  
5 with a low or zero magnetic field.

Finally, apart from these oscillation and diffusion movements, charged particles move along or around permanent magnets, perpendicular to the plane that contains the "magnetic field" vectors generated by the magnetic  
10 structure. This is why it is preferable to close the magnetic field structures on themselves to avoid losses of charged particles at the ends of the magnetic structures. The result is then a "magnetron" type structure.

#### 15 State of the art

Several alternating polarity geometries are possible for a multipole confinement.

A first conventionally used geometry is shown on Figure 2. This type of multipole structure is called a  
20 "continuous linear structure". It presents an alternation of continuous permanent magnet lines 3 to the plasma. In Figure 2, the polarity is alternated along a direction marked as reference 2. The continuous polarity lines extend along a direction marked as reference 1, this direction  
25 being perpendicular to the direction of alternation 2.

Figure 3 shows another possible geometry. This is a "checkerboard" structure, which has a discontinuous alternation along two directions 1 and 2. The magnets are no longer arranged in continuous lines, each magnet has a

different polarity from its neighbours along directions 1 and 2.

A third possible geometry is shown in Figure 4. This shows the alternation "in interrupted line". This structure  
5 uses the principle diagram of the structure in Figure 2, but the magnets on polarity lines are at a spacing from each other.

The publications by R. Limpaecher and K.R. MacKenzie, Rev. Sci. Instrum., vol. 44, P. 726-731 (1973), and  
10 K.N. Leung, T.K. Samec, and A. Lamm, Phys. Lett., vol. 51A, p. 490-492 (1975), divulge confinement devices using the structures described in Figures 2 to 4.

In these devices, the permanent magnets are arranged inside and outside the confinement chamber, but the magnets  
15 still have one of the poles of each magnet located on a wall of the chamber.

Figure 5 diagrammatically shows a cross section of an example device divulged in the said publications. It comprises a chamber 10 comprising a wall 2, plasma 5  
20 confined in the chamber 10 by means of permanent magnets 3. In this example, the magnets are located outside the chamber, but it can be seen that at least one pole of each magnet 3 is on the wall 2. Magnetic field lines are shown diagrammatically by arcs of circles 6 and 7. The  
25 magnetisation lines 7 loop back on themselves and intercept the wall 2.

The different magnet structures may be used on the device in Figure 5. For example, the structures in Figures 2 to 4 can be used along direction 1 shown in Figure 5.

Direction 1 is then perpendicular to the plane of the figure.

The structures can also be used along another direction, namely direction 1 can be placed along the transverse plane of the chamber as shown in Figure 6, using the structure in Figure 2 as an example.

A first embodiment according to Figure 5 or 6 shows a structure according to Figure 2. With reference to Figure 2, it can be seen that no magnetic field line 7 of a permanent magnet loops back along direction 1 on the back face of the same magnet, since the structure is continuous along this direction.

However, festoon losses (mechanism 2), trapping losses (mechanism 3), and wall losses are very high with this structure. They are linear.

Line 11 represents losses of charged particles that strike the pole of a magnet or the wall facing the said pole (maximum magnetic intensity).

Line 12 represents losses of charged particles that strike the wall between two poles with opposite polarity (minimum magnetic intensity).

Lines 11 and 12 can be seen in the cross-section in Figure 5.

A second embodiment according to Figures 5 and 6 uses a structure as shown in Figure 3.

The field lines 7 that loop back onto the same permanent magnet 3 intercept the wall 2 of the chamber 1. Therefore, there are isolated losses by mechanisms 2 and 3.

Points 11 in Figure 3 correspond to festoons, and also to paths of particles trapped on field lines 7 by mechanism

3. Consequently, particles oscillating on a field line looping back on the same magnet 3 or arriving at a festoon will be intercepted by the wall 2 of the chamber and are lost for the plasma.

5        In checkerboard structures, festoons and impact points 12 of particles trapped on lines 6 are isolated and also correspond to geometric centres of the faces of permanent magnets. Therefore, losses are relatively low compared with the first embodiment.

10       In the checkerboard magnetic configuration, only charged particles reflected by mechanism 1 are actually confined by the magnetic field created by the series of permanent magnets.

15       A third embodiment shown in Figures 5 and 6 uses a structure according to Figure 4.

It shows a case intermediate between the previous two cases, with a confinement efficiency intermediate to the two others.

20       There is a loopback of field lines on the back of the magnet along direction 1. Therefore, charged particles are intercepted by the wall of the chamber. These interceptions of particles by the wall according to mechanism 3 are represented by crosses 11.

25       Isolated losses by mechanisms 2 and 3 take place along direction 2.

There are other disadvantages with the structures described above, apart from the plasma losses mentioned above.

There are three main disadvantages.

1/ It is difficult to make and to use "magnetron" type structures closed on themselves, since the said structures avoid plasma losses at the ends of continuous structures.

2/ It is difficult to insert non-linear magnetic structures in a vacuum chamber. Thus, only some chamber geometries are suitable for containing simplified linear magnet structures such as cylindrical or parallelepiped shaped structures.

3/ Continuous magnet lines require large quantities of heavy and expensive permanent magnets.

#### Presentation of the invention

The invention proposes to overcome these disadvantages.

15 The invention proposes a multipole magnetic confinement structures for overcoming these disadvantages, while providing a very high confinement efficiency for charged plasma species.

Therefore, the invention proposes a device for  
20 confinement of plasma in a chamber comprising means of creating a magnetic field, the said means comprising a series of permanent magnets capable of creating a magnetic field presenting a multipole alternating magnetic structure to the plasma, characterised in that the magnets are  
25 capable of confining the plasma in a large volume, the magnets being discontinuously distributed around the volume, and in that the magnets are arranged inside the chamber, at a distance from the walls of the chamber held in place by support rods, the support rods extending along  
30 the axis of magnetisation of the said magnets and being

arranged so that they are centred on the poles of the permanent magnets.

The invention is advantageously complemented by the following characteristics, either individually or in any  
5 technically possible combination:

- the support rods extend perpendicular to the walls of the chamber;

- the series of permanent magnets is in a discontinuous checkerboard type structure;

- 10 - the series of permanent magnets is in a discontinuous structure with interrupted line;

- the permanent magnets have a symmetry of revolution;

- the permanent magnets are cylindrical;

- 15 - the cross-section of the rods is small compared with the dimensions of the permanent magnets;

- the support rods are tubes, the permanent magnets being located inside the tubes in the end extending into the chamber, each magnet comprising a plate or a disk made  
20 of a material with high magnetic permeability on its face furthest back from the inside of the chamber;

- the material is soft iron;

- it comprises means of cooling the permanent magnets;

- 25 - the cooling means comprise a supply-return circulation circuit for a fluid around each magnet, this circuit comprising a duct passing through the centre of the magnet;

- the permanent magnets are contained in an external protective enclosure that contains a non-magnetic conducting or dielectric material;

5 - it comprises means of producing plasma that are independent of the confinement means;

- the plasma production source is a structure with excitation by thermo-emissive filaments;

10 - the plasma production source is a structure excited by application of an electric voltage with a given frequency and shape, to the gas;

- plasma production means contain means capable of applying a microwave electric field to the gas;

- it comprises plasma production means that use at least a part of the confinement means;

15 - the plasma production means are capable of applying an electric voltage with a determined frequency and shape to the confinement structure;

- the plasma production means include means capable of applying an electric microwave field to the gas.

20

#### Presentation of the figures

Other characteristics, purposes and advantages of the invention will become clearer from the following description that is purely illustrative and is non-  
25 limitative, and that should be read with reference to the appended drawings, wherein:

- Figure 1, already commented on, shows the path of a charged particle between two mirror points M located on the face of permanent magnets with an alternating polarity;

- Figure 2, already commented on, shows a geometry of a multipole structure along a continuous line;

- Figure 3, already commented on, shows an alternating checkerboard multipole structure;

5        - Figure 4, already commented on, shows a multipole structure along a discontinuous or interrupted line;

- Figure 5, already commented on, shows a cross section through a chamber according to the state of the art using the structures in Figures 2 to 4;

10       - Figure 6, already commented on, shows a cross section through a confinement device with a multipole structure along a continuous line;

- Figure 7 diagrammatically shows a cross section through a general structure of a confinement device 1  
15 according to the invention;

- Figure 8 shows a detailed view of three permanent magnets 3;

- Figure 9 diagrammatically shows a longitudinal section through the structure of the permanent magnet  
20 cooling means;

- Figure 10 is a cross sectional view of a variant of the invention including materials with high magnetic permeability in which the permanent magnets are inside support tubes;

25       - Figure 11 diagrammatically shows a front view of a checkerboard structure according to the invention, on which isolated festoons are shown.

#### Description of the invention

Refer to Figures 7 and 8 that illustrate a possible embodiment of the invention.

Figure 7 shows a cross section through the general structure of the confinement device. The device comprises a chamber 1 comprising a wall 2 and several permanent magnets 3 arranged in the said chamber 1. Plasma 5 fills the inside of the chamber 1 and is confined in the said chamber.

Figure 8 shows details of three permanent magnets 3.

The plasma 5 may be produced by any plasma source (not shown) located around the periphery of or inside the chamber, and operating within a pressure range of less than a few  $10^{-2}$  torr.

Firstly, the plasma 5 may be produced by means independent from the confinement means.

For example, the plasma 5 could be produced by excitation by filament. In this case, electrons are emitted by thermo-emissive filaments internal to the confinement structure and negatively polarised with respect to the chamber and the magnetic structure.

Devices can also be used enabling application of an electric voltage to the gas, to generate the low pressure plasma. The electric voltage may have a variety of shapes and frequencies depending on the application. For example, the electric voltage may be DC, pulsed DC, low frequency or radio frequency.

The plasma may also be excited by application of a microwave electrical field to the gas. The microwave field may be accompanied by a magnetic field, and for example it may be an excitation by electronic cyclotron resonance (ECR). The microwave field may also not be accompanied by a

magnetic field, and a surface wave excitation can then be used.

The plasma can also be excited by magnetron excitation.

5        It is also possible to use all or some magnetic confinement structures to excite the plasma, either by application of a DC voltage or a pulsed DC voltage, or a low frequency voltage or a radio frequency voltage, to the structure; or by application of microwaves, for magnetic  
10    field excitation (for example ECR) or by surface wave.

      Thus in all cases, any plasma excitation type is possible regardless of the excitation frequency and the excitation mode (for example ECR, continuous discharge, pulsed continuous discharge, low frequency discharge, radio  
15    frequency discharge, surface wave, inductive discharge or magnetron discharge or ECR).

      The plasma reactor described in this application includes required plasma pressure measurement and diagnostic means (not shown in the figures).

20       Similarly, chamber 1 is equipped with a large number of gas inlet and pumping devices not shown but known in themselves, to maintain the gas pressure to be ionised at a required value and that may for example be equal to  $10^{-6}$  torr or less, up to  $10^{-2}$  torr, for example, depending on  
25    the nature of the gas and the excitation frequency.

      The magnets 3 are fixed to the chamber 1 by support rods or tubes 4 centred on the pole of each magnet and along the line of the magnetisation axis of each magnet.

      According to one possible embodiment of the invention,  
30    the diameter of the supports 4 are very small compared with

the dimensions of the magnets 3, and extend perpendicular to the walls 2 of the chamber 1, the said walls 2 extending towards the inside of the chamber 1.

According to another embodiment of the invention, for example shown in Figure 10, the supports 4 may have approximately the same diameter as the magnets. Plates or disks 18 with a high magnetic permeability are then provided.

Similarly, according to another embodiment not shown in the figures, the supports do not need to be perpendicular to the walls 2 of the chamber 1, but may be arranged skew to the walls.

Preferably, the permanent magnets 3 have magnetisation axes oriented alternately in one device and then the next. The result is then a multipole structure with fast, almost exponential decay of the intensity of the magnetic field as a function of the distance from the magnets.

Figure 8 shows the magnetic field lines created by the permanent magnets 3, as solid lines 6, 7 and dashed lines 8.

It can then be seen that the permanent magnets are fixed at a distance from the walls 2 of the chamber 1 such that the walls 2 are outside the effective influence area of the magnets enabling charged particles output from the plasma 5 and trapped in the magnetic field on the lines 7, to oscillate freely within the interval between two elastic or inelastic collisions between particles, without obstacle between two mirror points M with the same magnetic field intensity.

Furthermore, field lines 8 located between the wall 2 and the permanent magnets 3 have a very low probability of trapping charged particles output from the plasma. Charged particles are reflected by field lines 6 located on the side of the plasma 5.

Therefore, there is a very small probability that a charged particle trapped in a field line will meet a wall. Therefore plasma losses by collision with the chamber walls are minimised.

Figure 8 shows that the festoons 12 of such a device on the faces facing the plasma 5 are identical to the isolated festoons of a discontinuous checkerboard structure (Figure 3) or an interrupted line structure (Figure 4). Therefore, festoon losses are less than in a continuous structure (Figure 2).

According to a first possible embodiment, the sections of the supports 4 are very small (for example small diameter). Consequently, intersections with magnetic field lines 7 are minimised. The result is thus ideally an intersection dimension 13 between oscillating particles and lines 7 approximately equivalent to a dimension of an isolated festoon 12.

According to one embodiment shown in Figures 7 and 8, each magnet is composed of a cylindrically shaped magnet with axial magnetisation that is located approximately along the extension of the axis of the support 4.

The fact that the magnets have a symmetry of revolution about the magnetisation axis enables the magnet to represent a perfect "magnetron" type structure all by itself. In this way, particles trapped on the high

intensity field lines 7, in other words looping back onto the pole opposite the same magnet, can be diverted around the axis of the magnet without obstacle.

The preferred cylindrical shape has the advantage that  
5 it is easier to make than a spherical shaped magnet, but especially it is easier to encapsulate in a sealed enclosure.

Encapsulation in a sealed enclosure is often necessary firstly to prevent plasma contaminations and / or corrosion  
10 of magnets by the plasma, and secondly to cool the magnet if necessary.

Obviously, magnet encapsulation and attachment materials are made from non-magnetic materials. For example, non-magnetic metals could be used.

15 If it is necessary to cool the permanent magnets (which is the case particularly for applications with dense plasmas), this can be done by fluid circulation in two directions by the use of a tube 4 for attachment of each magnet 3.

20 An example of such encapsulation is shown in Figure 9. According to this preferred embodiment, each support 4 may be used to assemble an inlet duct 14 carrying a cooling fluid. It extends along a central bore formed in the magnet 3 along the magnetisation axis of the magnet. This duct 14  
25 made in the form of a tube communicates at its end with a chamber 15 delimited between the magnet 3 and an enclosure 16 surrounding the magnet at a distance from it.

The chamber 15 opens up into a cooling fluid return duct 17 delimited between the inlet duct 14 and the support  
30 4.

The magnet 3 is thus encapsulated by the protective enclosure 16 enabling circulation of a cooling fluid around the magnet 3. For example, the magnet encapsulation material and the material forming the supports 4 are made  
5 from a good conducting non-magnetic material (non-magnetic metals) but they can also be surrounded by dielectric materials for contamination reasons, without preventing the device from operating correctly.

One variant illustrated in Figure 10 of the device  
10 according to the invention consists of using an attachment and support tube 4 with a constant diameter equal to approximately the diameter of the permanent magnet. This attachment tube 4 fixes and encapsulates the magnets. Each permanent magnet is located in the end of the tube that  
15 extends in the plasma. The permanent magnets are cooled if necessary.

In this variant, trapped particles are able to oscillate freely between points M.

According to this variant, each permanent magnet 3  
20 located in a tube 4 is made from a material with a high magnetic permeability 18 (for example such as a soft iron plate or disk) on its polar face furthest from the plasma. In this configuration, the electrons may also oscillate between two mirror points M. One of the points M is no  
25 longer facing the pole of the magnet, but is on the side along the support 4, while the other point M remains facing the pole. Thus, the presence of the plate or the disk 18 on the outermost face from the plasma 5 is used to modify the position of the mirror points M associated with the poles  
30 of each permanent magnet 3, in space.

These magnetic structures have very good plasma confinement efficiency, and may be adapted to a very wide variety of chamber geometries, for example cylindrical geometries as shown in Figure 7.

5

#### Advantages

The described devices can give very good plasma confinement efficiency.

They minimise losses of charged particles by the  
10 different mechanisms. In particular, as shown in Figure 11, festoon losses are reduced. In the checkerboard structure used in possible embodiments of the invention, field lines  
6 form a protective barrier on which particles are reflected or oscillate. Points 11 and 12 on Figure 11 show  
15 isolated festoons. Thus in this type of structure, on average there are only two isolated festoons per permanent magnet, instead of a complete line of festoons on a continuous structure.

Furthermore, each permanent magnet forms a perfect  
20 three-dimensional magnetron structure due to its symmetry of revolution, which correspondingly limits losses of charged particles and also makes the plasma perfectly stable.

Moreover, multipole structures proposed by the  
25 invention are very easy to use. They only require a very small number of permanent magnets compared with a continuous linear structure, which makes important cost and weight savings for large volume chambers.

Multidipole magnetic structures proposed by the  
30 invention use magnets with the same nature (for example

made of barium strontium ferrite, samarium-cobalt, neodymium-iron-boron) and with the same dimensions (unit magnets with dimensions of approximately one centimetre, distance between magnets equal to a few centimetres) as in  
5 conventional multipole structures.

As non-limitative examples, this type of multidipole confinement structure may be made with samarium-cobalt magnets 2 cm in diameter and 3 cm long, with one every 7 cm around the periphery of a cylindrical chamber.

10 The device according to the invention is advantageously used in Plasma Based Ion Implantation (PBII), direct or reactive plasma assisted sputtering, microwave plasma assisted Chemical Vapour Deposition (CVD), etching, or even thermochemical treatments.

15 Note also their application to sputtering of magnetic materials, dielectric deposits with high permittivity, for example such as grid oxides in microelectronics.